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ABSTRACT

Currently, many environmental tests are based on shock spectrum and the test specifications frequently require a slowly swept sinusoidal input. For this type of test, the input amplitude required to produce a response equivalent to that resulting from a transient is highly dependent upon the damping of the system under test. The procedure which is usually followed is based on a single value of damping and results in a considerable overtest of low damped systems.

This paper proposes a test method which accounts for the variation of response with damping. The test input consists of a spaced sequence of sinusoidal pulses. The frequency, amplitude, and number of cycles of each pulse are selected to adequately meet specified shock spectra for various levels of damping. Application of the method to a realistic test specification indicates a significant improvement over slow sweep procedures.

INTRODUCTION

Many current environmental vibration tests intended to simulate transients are based on shock spectra. The specifications frequently require a slowly swept sinusoidal input with the amplitude controlled to produce responses that meet a specified shock spectrum based on only one value of damping. One disadvantage of this type of test is

that the input amplitude required to produce the desired response at a particular frequency is highly dependent upon the damping of the system under test. In order to avoid undertesting, the input amplitude is usually based on the highest value of damping which is present. As a result, systems with low values of damping are severely overtested.

This paper presents a test method which overcomes the above difficulty. The test method produces response levels which adequately meet specified shock spectra for various levels of damping.

SLOW SWEEP TEST

Consider the system shown in figure 1. The equations of motion are

$$\ddot{x}_i + 2\lambda_i \omega_i (\dot{x}_i - \dot{x}_B) + \omega_i^2 (x_i - x_B) = 0, \quad i = 1, \dots, N \quad (1)$$

where

$$\omega_i = \sqrt{\frac{k_i}{m_i}}$$

$$\lambda_i = \frac{c_i}{2\sqrt{k_i m_i}}$$

It should be noted that the results of this paper are applicable only to systems of the form illustrated in figure 1. As shown in reference 1, the results should not be applied to other systems, such as more general multidegree-of-freedom systems.

$$y_i = x_i - x_B$$

Then equations (1) become

$$\ddot{y}_i + 2\lambda_i \omega_i \dot{y}_i + \omega_i^2 y_i = -\ddot{x}_B \quad (2)$$

Damping is frequently specified in terms of Q , which is defined as

$$Q = \frac{1}{2\lambda}$$

In the shock spectrum method, the initial conditions for equations (2) are assumed to be

$$y_i(0) = \dot{y}_i(0) = 0 \quad (3)$$

The response shock spectrum for a particular motion input to a system is determined from the maximum response of a single-degree-of-freedom system having a given damping and frequency. The maximum response is found for several single-degree-of-freedom systems having the same damping but different frequencies. These maximum responses may then be plotted versus frequency to determine the shock spectrum. For environmental vibration test specifications the maximum absolute acceleration is the variable usually considered. The test specification is obtained by enveloping the shock spectra of **all** significant flight inputs.

The input which is used in the environmental vibration test is that required to produce responses equal to or greater than the desired response shock spectrum. In this paper, all inputs are acceleration time histories at the base of the system (\ddot{x}_B).

A slowly swept sinusoidal test input is frequently used to satisfy the above requirements. The amplitude is adjusted to satisfy the test specification. For this type of test, the input amplitude required to produce a desired response at a particular frequency is highly dependent upon the damping of the system at that frequency. Although the input amplitude of a slow sweep test can be adequately specified for one particular value of damping, the input amplitude so selected is inadequate for any other value of damping. Some examples which illustrate this point are shown in figures 2 to 4. In figure 2, the solid lines indicate response levels to flight inputs for three different assumed values of Q . These response levels are similar to those obtained in deriving test specifications for Lunar Orbiter. Although the flight response levels for Q 's of 10 and 30 are shown as a single curve, actually the levels for a Q of 30 are very slightly higher than those for a Q of 10.

The upper dashed line in figure 2 is the response level for a slow sweep test input which is adjusted to produce conservative responses in systems having a $Q = 30$. If the systems being tested actually have a Q of 30, then this input test level produces response levels which are adequate. However, if the systems being tested have a Q of 5 or 10, then the response levels are seen to be too low. Hence, the test levels are too low.

Figure 3 shows the shock spectra for a test input adjusted to produce conservative responses in systems having a Q of 10. As figure 3 indicates, if the systems being tested actually have a Q of 10, then this test input produces adequate response levels. If the systems being tested have a Q of 30, the response levels are much

higher than desired; if the systems being tested have a Q of 5, the response levels are too low.

In order to assure adequate response levels for all three values of Q , the amplitude of the slow sweep test input must be based upon a Q of 5. The response levels for this case are shown in figure 4. As the figure indicates, the response levels for systems with a Q of 10 are almost twice as high as the flight response levels for a Q of 10 and the response levels for systems with a Q of 30 are more than five times higher than the flight response levels for a Q of 30. Thus, systems with Q 's of 10 and 30 are severely overtested.

For systems of the type shown in figure 1, several of the springs and masses may have the same natural frequency, but the values of damping may be different. Also, the damping of a particular system may not be accurately known. In these situations, it is highly desirable to have a test input which will produce adequate response levels for various values of damping without severely overtesting any system. As the above examples have shown, a slowly swept sinusoidal test input cannot accomplish this objective.

SINUSOIDAL PULSE TEST

The above overtesting can be overcome by testing at a sequence of discrete frequencies instead of using a continuous sweep. For a particular input frequency, the response of a system to a sinusoidal input is dependent upon the number of cycles of input. If the number

of cycles of input is numerically equal to the Q of the system, then essentially steady state conditions are obtained. If the number of cycles of input is less than the Q of the system, then the variation of the response with damping will be shown to be less significant. A system with a natural frequency of 20 Hz was subjected to a varying number of cycles of sinusoidal input with a frequency of 20 Hz. Figure 5 shows the variation of the maximum response as a function of the number of cycles of sinusoidal input for four different values of Q . For one cycle of input, the maximum response of the system is practically the same for all values of Q shown. As the number of cycles of input is increased, the curves begin to disperse until the steady state values are reached. This phenomenon can be used to provide an environmental vibration test which accounts for the variation of response with damping.

As an example of the procedure, suppose that response shock spectra envelopes of flight data have been computed for Q 's of 5, 10, and 50. Suppose, further, that the shock spectrum levels for a Q of 10 are 50 percent higher than the levels for a Q of 5 and the levels for a Q of 50 are twice as high as the levels for a Q of 5. An inspection of figure 5 indicates that for a system with a natural frequency of 20 Hz, 4 cycles of sinusoidal input will produce the desired variation with damping. The input amplitude is selected so that test levels are higher than specification levels for all 3 values of damping. Curves similar to those in figure 5 are easily obtained for other values of frequency and damping.

APPLICATION

The procedure has been applied to the test levels given earlier. Since, as shown by the flight data in figure 2, the required response levels are very nearly the same for $Q = 10$ and $Q = 30$, and only 20 percent less for $Q = 5$, it is believed that this example is as difficult a case as would ordinarily be encountered.

As indicated by figure 5, the test input may consist of a single cycle at each of the necessary frequencies since the specification levels are practically equal for all three values of Q over the frequency range considered. The actual discrete frequencies used for the test input were selected as explained below. The only requirement is that the shock spectrum of the test input be at least as high as the specified levels for all three values of Q . The following procedure was used to determine the test input. An input frequency was selected and the shock spectra were computed for the three values of Q for a single cycle of input with 1 g amplitude. Based on this information, an input amplitude was selected which produced responses slightly higher than the required levels over a small frequency range. This process was continued until the entire frequency range had been covered. Note that the results are essentially a first try. No attempt was made to determine the optimum combination of test frequencies and amplitudes. The final test input is a series of 16 sinusoidal pulses, each pulse consisting of single cycle sine wave with a specified frequency and amplitude. The actual frequencies and amplitudes are shown in table 1 along with the frequency range tested by each pulse.

In order to avoid superimposing the responses from consecutive pulses, the pulses must be spaced a short time apart. The space between consecutive pulses should be based on the highest value of Q . Preliminary studies indicate that between consecutive pulses the systems being tested should be allowed to undergo a number of cycles about equal to twice the highest value of Q . For example, in the present case, the time between pulses should be long enough to allow the systems being tested to undergo about 60 cycles of oscillation. With this spacing the total test required slightly less than .5 minute, which is approximately $1/3$ of the time required by a 4 oct/min sinusoidal sweep.

The results are shown in figures 6 to 8. Note that for all three values of Q over the frequency range considered the shock spectra for the test input are slightly higher than the required levels. Comparison of these results with the slow sweep levels indicates a significant improvement. The sine pulse test produces response levels which are very nearly proportional to the levels received from flight inputs. All systems are conservatively tested, but no system is subjected to a drastic overtest.

CONCLUSIONS

A test method which accounts for the variation of shock spectra with damping has been presented and applied to a realistic test specification. The test consists of a spaced sequence of sinusoidal pulses with the frequencies and amplitudes selected to meet specified shock spectra for different values of damping. The results indicate a significant improvement over slow sweep procedures.

REFERENCE

1. Howlett, James T. and Raney, John P.: A New Approach for Evaluating Transient Loads for Environmental Testing of Spacecraft. Shock and Vibration Bulletin No. 36, Part 2, Jan. 1967, pp. 97-105.

TABLE I.- TEST INPUT

Input frequency, Hz	Input amplitude, g	Frequencies tested, Hz
5	1.90	5 - 7
8	1.98	8 - 10
14	2.33	12 - 18
20	2.36	20 - 24
26	2.48	26 - 30
32	2.63	32 - 38
40	2.80	40 - 48
50	2.93	50 - 62
64	3.05	64 - 86
88	3.05	88 - 120
122	3.05	122 - 166
168	3.05	168 - 210
230	3.30	212 - 260
280	3.58	262 - 296
325	3.90	298 - 374
400	4.20	376 - 400

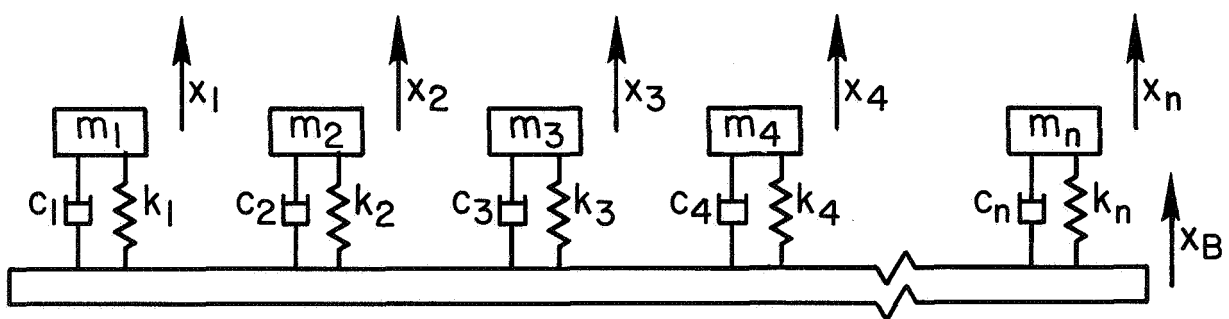


Figure 1.- Physical system.

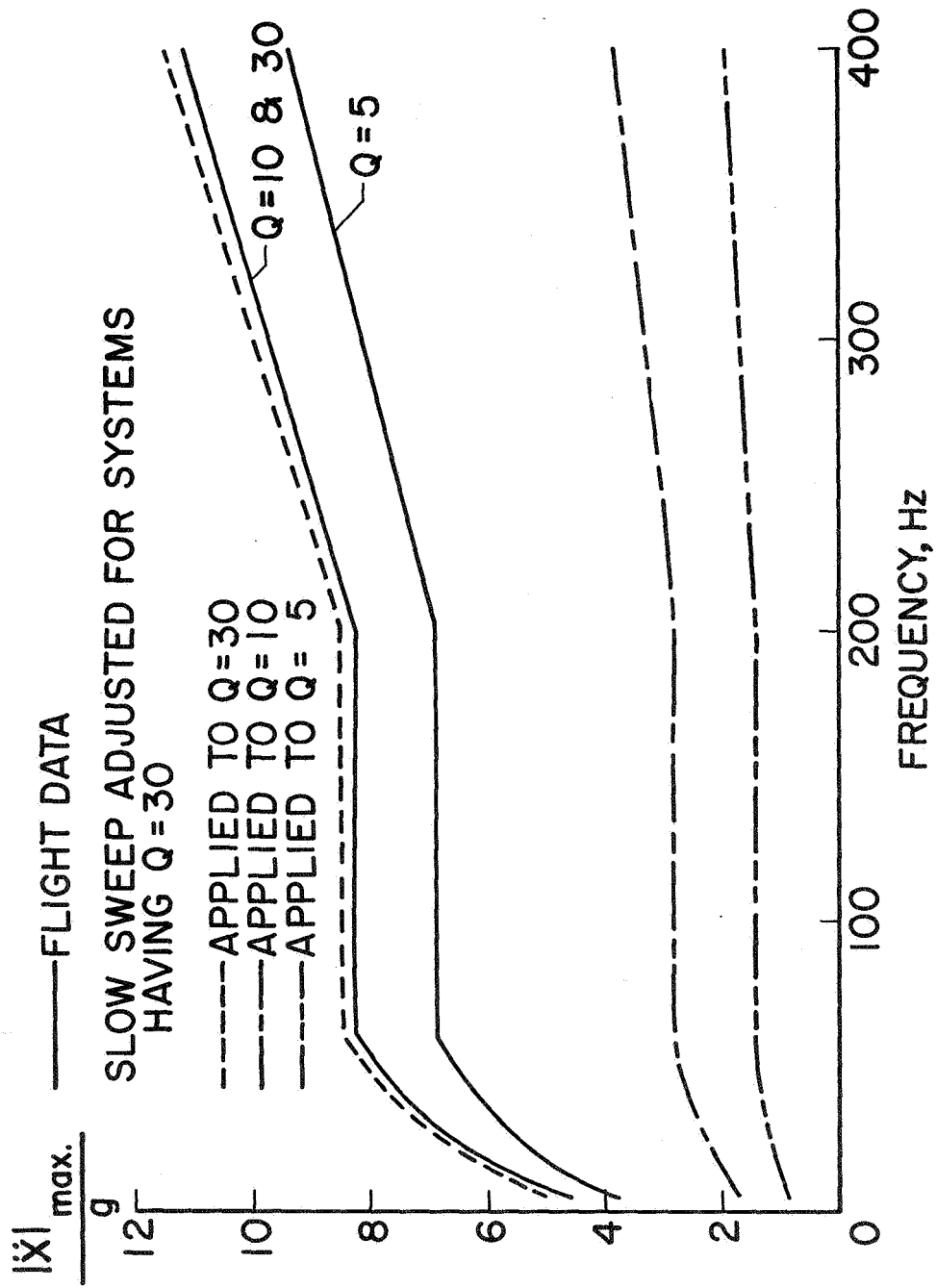


Figure 2.- Shock spectra of slow sweep adjusted for conservative response in systems having $Q = 30$.

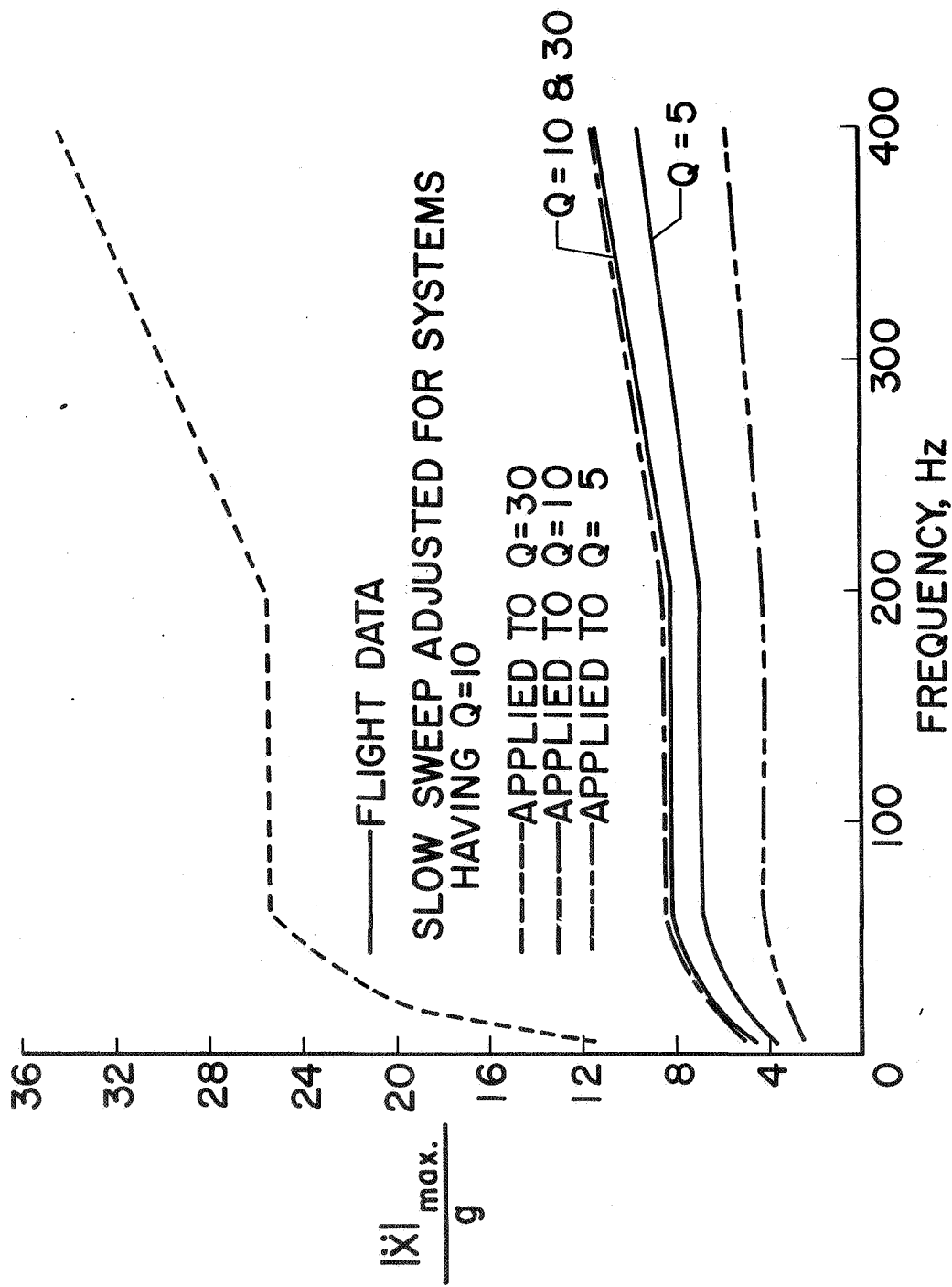


Figure 3.- Shock spectra of slow sweep adjusted for conservative response in systems having $Q = 10$.

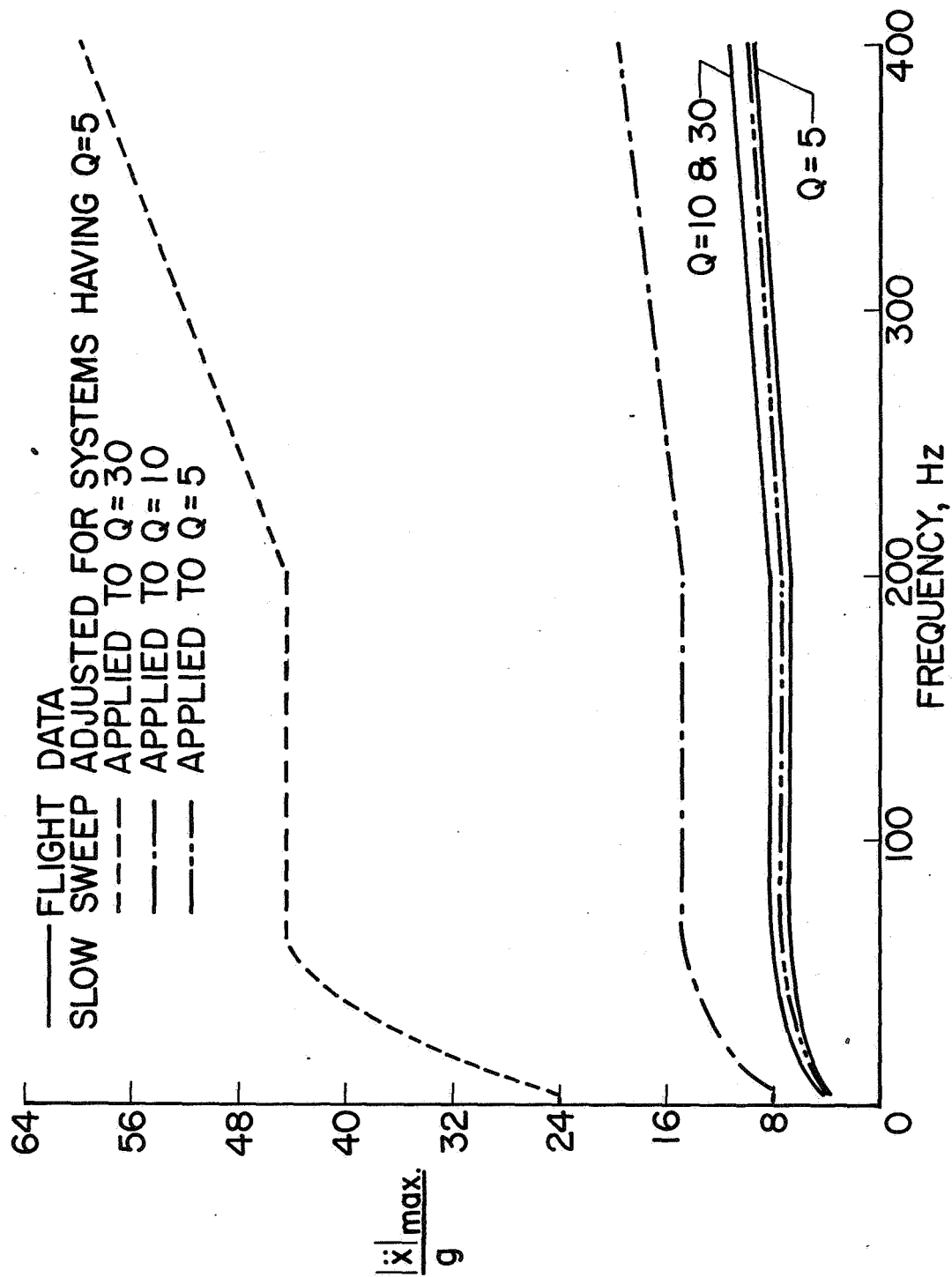


Figure 4.- Shock spectra of slow sweep adjusted for conservative response in systems having $Q = 5$.

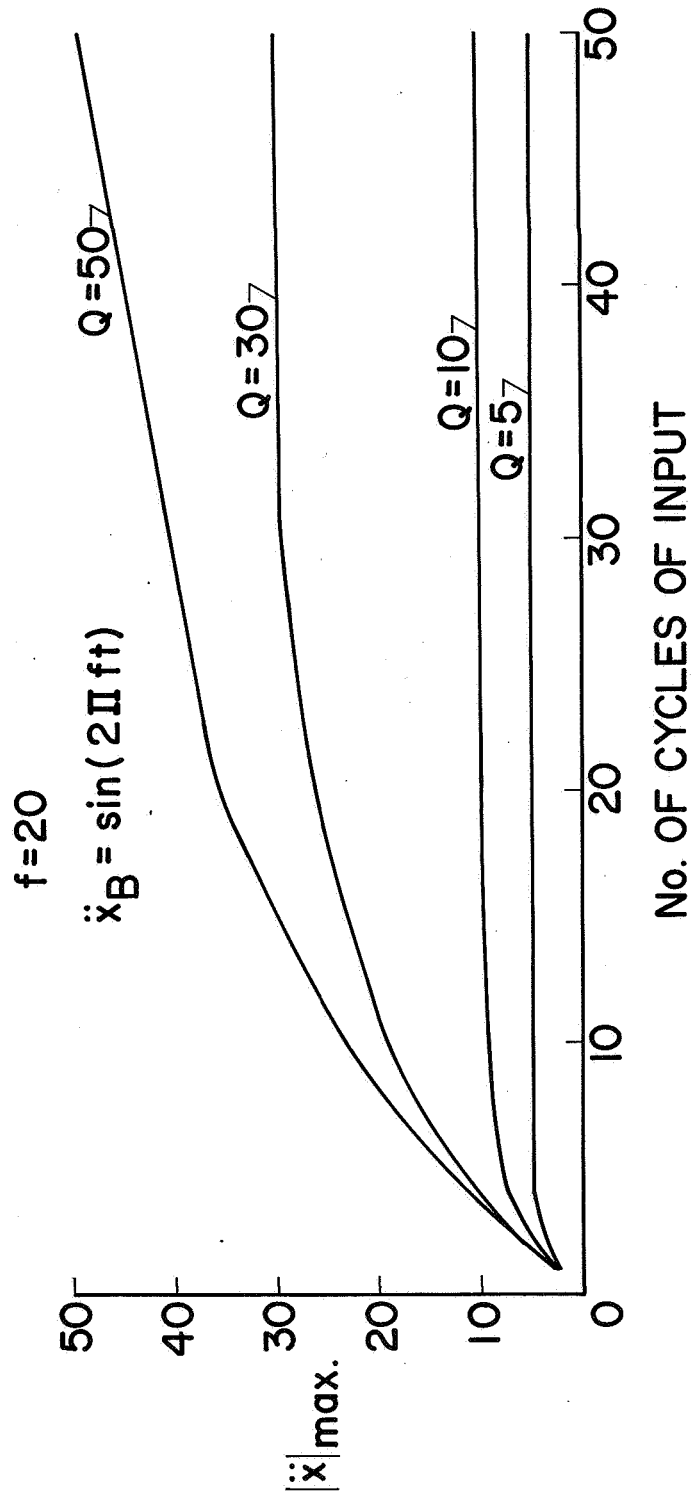


Figure 5.- Variation of maximum response with number of cycles of input for various values of Q .

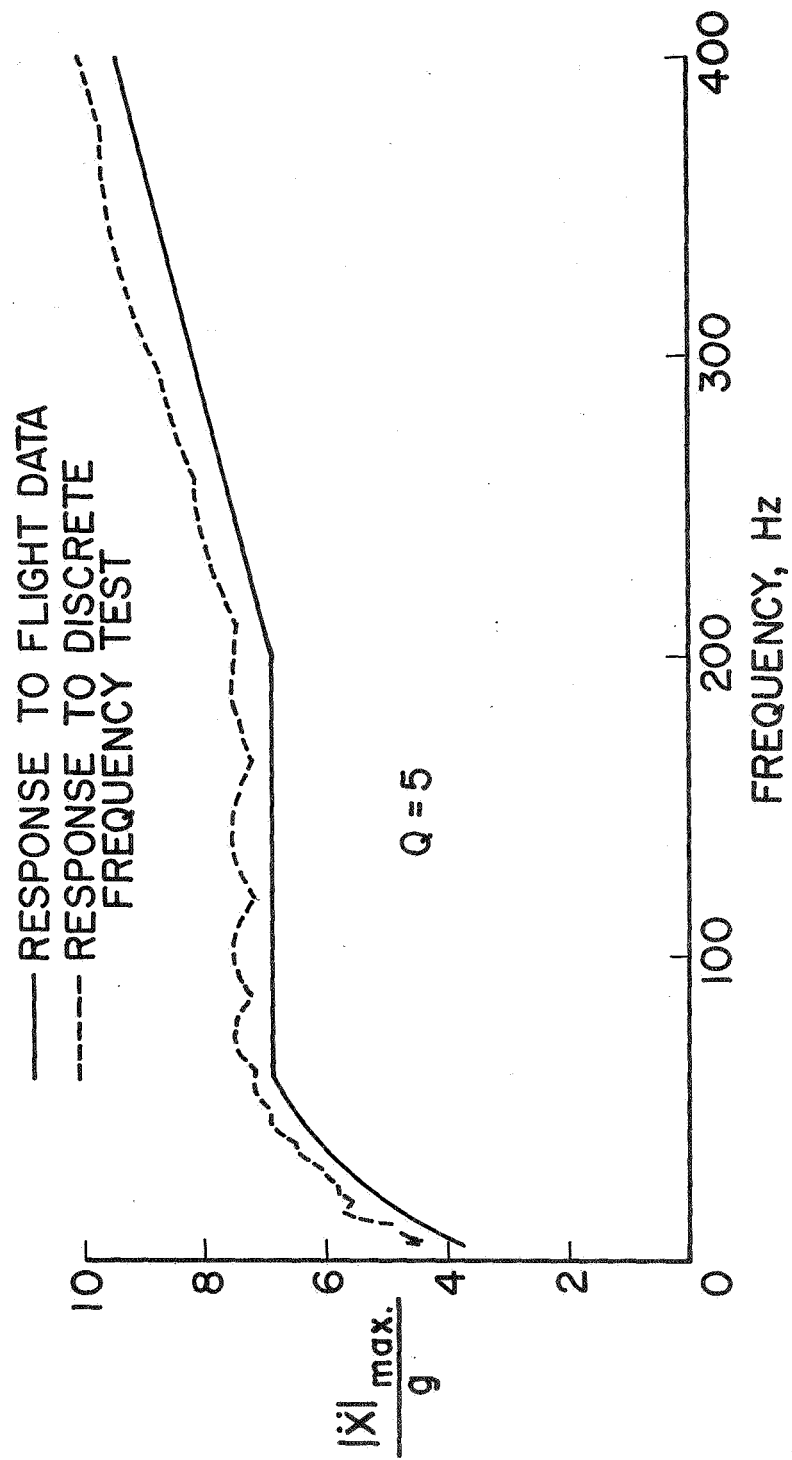


Figure 6.- Shock spectrum with $Q = 5$ for discrete frequency input.

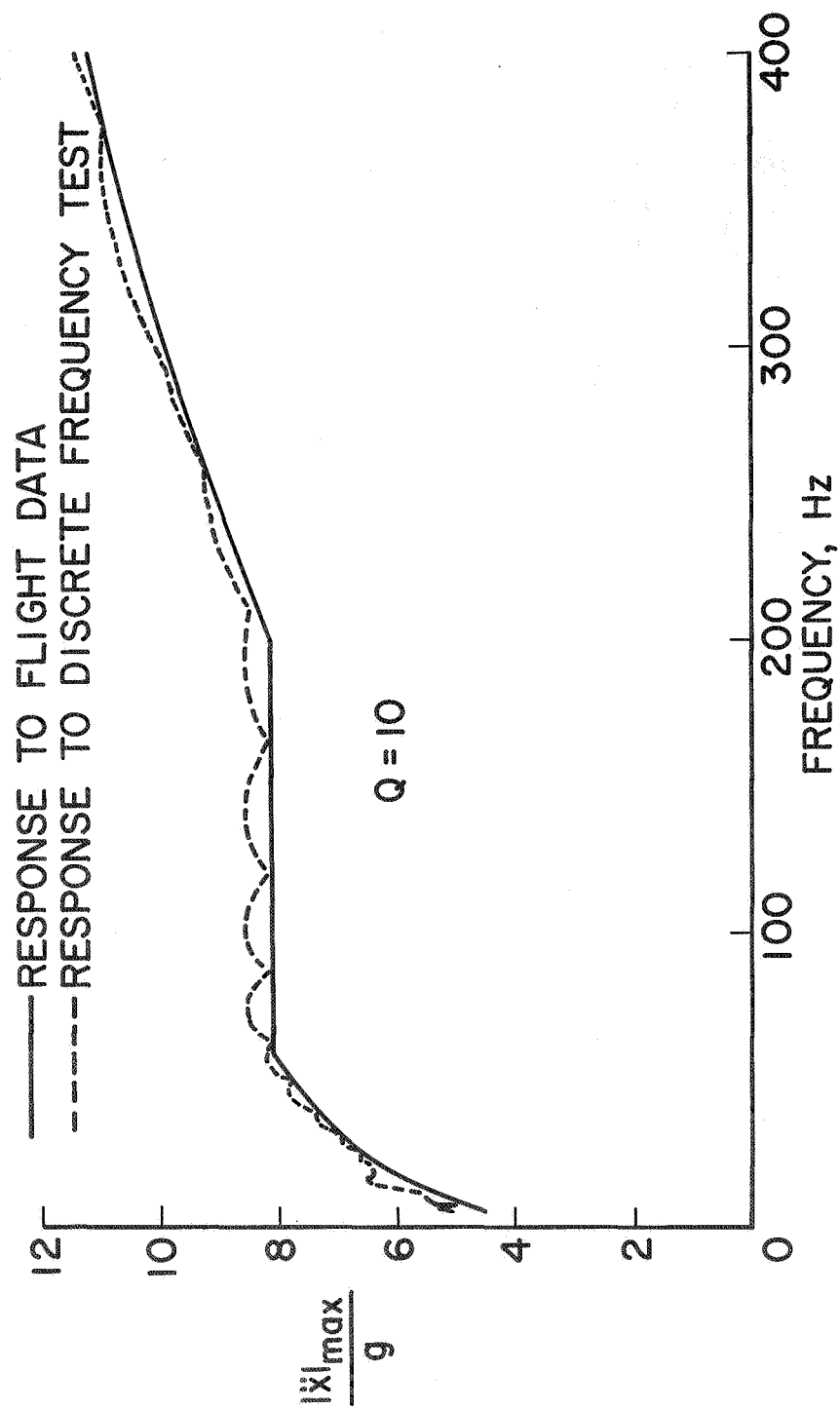


Figure 7.- Shock spectrum with $Q = 10$ for discrete frequency input.

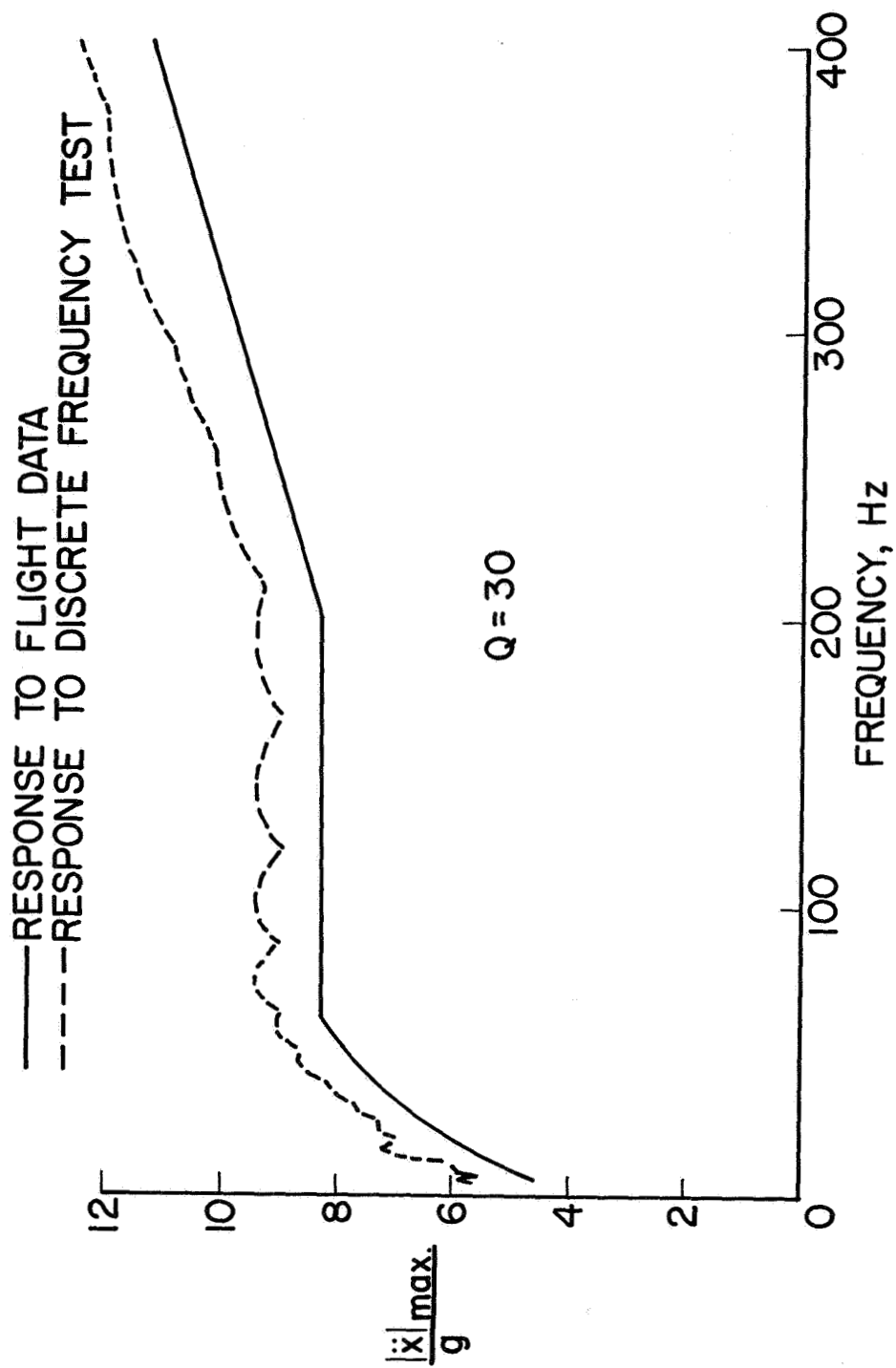


Figure 8.- Shock spectrum with $Q = 30$ for discrete frequency input.